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19960409 050

NAIC- ID(RS)T-0098-96

HUMAN TRANSLATION

NAIC-ID(RS)T-0098-96 26 March 1996

MICROFICHE NR: 96C000276

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English pages: 22

Source: Cama, China Astronautics and Missillery Abstracts,
Vol. 2, Nr. 4, 1995; pp. 1-8

Country of origin: China

Translated by: Leo Kanner Associates
F33657-88-D-2188

Requester: NAIC/TASC/Richard A. Peden, Jr.

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NAIC- ID(RS)T-0098-96

Date 26 March 1996

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ANALYSIS OF IR/mmW COMBINED SEEKERS

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【Abstract】 Features of combined seekers and their current development are reviewed. The IR/mmW dual-mode combined seeker and its key techniques are analyzed. The developing tendency of this seeker is described.

【Key Words】 IR imaging seeker Combined seeker IR seeker
Combined signal processing techniques

I. Foreword

With the growing complexity of the battlefield environments, rapid progress in optoelectronics, invisibility technology, and data processing capabilities, as well as continuous upgrading of flight vehicle performance and random ground wave interference on attacking tanks and armor from the air, it is required that the seeker system can operate normally in poor meteorological conditions and complex battlefield environments (fog, rain, snow, smoke, and dust), to distinguish false targets and to overcome interference from random background waves and electronic countermeasures, it is also required to have high capability in discriminating target with high guidance accuracy for the fire-

and-forget approach. In this situation and these requirements, the previous single-mode seeker system is unable to accommodate so that it is necessary to develop the dual- or multimode systems, so as to achieve higher capabilities of target detection probability, lower casualty rate and better resistance functions with lowering of false alarm rate. Therefore, by combining the sensors of different wavebands to form an independent target discriminator system is the most effective approach to satisfy the foregoing comments. Technically, combined homing seekers can be generalized into the following types: ultraviolet/infrared dual-spectrum combined seeker, passive infrared/active infrared combined seeker, visible light television/infrared imaging combined seeker, laser/infrared combined seeker, radiofrequency/infrared combined seeker, millimeter wave/infrared combined seeker, audio/infrared imaging or millimeter wave combined seeker, among others. The article will stress the analysis of millimeter wave/infrared combined seeker technology and with discussions in order to clarify the key technology of combined seekers.

II. Development Situation of Combined Seeker Technology Abroad

The Gulf War not only examined the effectiveness of various kinds of precision guidance weapons, but also pointed to the developmental direction of precision seeker device techniques of tactical missiles. In this war, all the possible guidance methods for operations were demonstrated in their missiles,

including beam guidance, infrared guidance, infrared imaging guidance, television guidance, radar command aiming line guidance, active radar homing guidance, wired guidance, and laser guidance. The combat ascertained the operational capabilities of these guidance approaches and also expected to further develop the new technology of homing devices.

As mentioned above, in development of missile homing device technology, the dual-mode or multimode combined seeker technology is a worthwhile research direction; preliminary development was carried out abroad. The Stinger Post applied an ultraviolet/infrared seeker; PbSe was applied in infrared (4.1 to 4.42micrometer band) and CdS applied in infrared (0.3 to 0.55micrometer band). The Mistral missile of France adopted the multielement infrared (InAs) ultraviolet combined seeker. The improved version of the Copperhead in the U.S. applied the laser semiactive, infrared imaging dual-mode combined seeker. Abroad, the missiles fitted with radar/infrared (RF/IF) dual-mode seeker have been successful, capable of effectively dealing with the antiship missiles (such as Flying Fish, and Styx) and antisubmarine aircraft with radio-frequency radar active homing device against sea-skimming aircraft. At present, with U.S. Navy support, the SIAM (automatic homing guidance air defense missile) completed principal theory-verification experiments in 1984. The shipborne antiship missile RAM was jointly developed by the U.S., the former West Germany, and Denmark. Besides SIAM and RAM, the Small Oak MIM-72 surface-to-air missile and the Sidewinder new-

version model AIM-9S Sidewinder of the U.S. applied the dual-mode combined guidance approach. In recent years, development also progressed in the millimeter/infrared dual-mode combined seeker. For millimeter wave technique used in combined homing apparatus, its tactical applications are mainly on passive homing. This technique utilizes the difference of the millimeter wave radiation intensities between target and background for target acquisition and discrimination; at present, the technique is applied mostly to two atmospheric windows of 35GHz (8mm) and 94GHz (3mm). By sharing in common a reflective mirror, combination of millimeter wave and dual spectrum infrared can be realized; or the combination of millimeter wave/infrared imaging is realized. For example, the EPHARM 155-mm terminal-guidance artillery round of West Germany, and the ASP 155-mm terminal-guidance artillery round adopt the millimeter-wave/infrared combined seeker. The audio homing device is developed as a component of the BAT dual-mode homing apparatus of the antiarmor terminal-guidance submissile of the U.S. Army. The BAT is the combined homing apparatus adopting audio/infrared dual-mode; the audio sensor in the BAT detects the audio signals of the target vehicles: by using audio to search the mobile targets, and by using infrared irradiation to detect the hot spots of targets. The code number of the BAT submissile is MGM-137, the ground launch missile system and the Army tactical missile system of long-range attack missiles of the three branches of the armed forces.

At present, development of new combined seeker technology has been more and more emphasized by many countries. In the near future, it is estimated that the U.S. and Western European countries will have deployed missiles of dual-mode seeker systems (or terminal-guidance artillery rounds).

III. Technical Features of Dual-Mode Combined Seekers

In multiple forms of combined seeker technique, in the author's view, the infrared/millimeter wave (IR/mmW) (including infrared imaging/millimeter wave, dual-spectrum infrared/millimeter wave, to be referred to below as infrared/millimeter wave) dual-mode homing guidance technique has the best performance. The IR/mmW dual-mode homing guidance technique is an optoelectronic dual-mode homing/guidance system with combined unification of infrared and millimeter-wave radar. In the system, optical and electronic techniques complement each other, to overcome their respective shortcomings, and to take advantage of optoelectronic guidance. In the following, the technical properties of IR/mmW combined homing heads are presented.

3.1. High adaptability in the battlefield

The IR/mmW dual-mode guidance system can automatically switch to optical or electronic guidance methods based on the battlefield and meteorological conditions, such as smoke, dust, and fog. The excellent penetration properties of millimeter waves supplement the disadvantages of the poor transmission

properties of infrared, thus enhancing the combat capabilities of the weapon system in various environmental conditions to carry out combat in all weather.

Table 1 lists the performance comparison and analysis of infrared type and millimeter wave type seekers. Table 2 lists the battlefield adaptation comparison of infrared, millimeter wave, and infrared/millimeter wave seekers.

TABLE 1. Comparison Between IR and mmW Seekers

IR Seeker	Millimeter-wave Seeker
Thermal radiation on surface of object detected	Radio waves reflected from detected object
High angular resolution power during tracking	Capable of searching large area with medium scanning rate
Better performance during rain and during chaff jamming	Better performance during weather with fog and floating particles
Discrimination power relative to flames, burning oil, and sunlight	With resolution for distance and target, or for one of the two
Disregarding radar corner reflector	Disregarding light and burning oil
Detecting capability is not related to target size	Affected by orientation angle during target detection

3.2. Shortening the time of accurate location of targets by the weapon system

Compared to infrared, the millimeter wave has a wider wavebeam, adaptable to search and intercept targets over a large area. After the millimeter wave radar intercepts a target, switching is conducted. Thus, the infrared system tracks and accurately locates the target in a small area already determined,

thus shortening the time for accurate location g of the target.

TABLE 2. Comparison of IR, mmW, and IR/mmW Combined Seekers in Different Field Conditions

战场条件 1	红外 2	主动毫米波	红外/毫米波
晴天 5	✓	✓ 3	✓ 4
烟雾、沙尘 6		✓	✓
雾 7		✓	✓
中雨 8	✓	✓	✓
干扰箔条 9	✓		✓
雷达角反射器	✓		✓
光点、油料燃烧 10	✓ 13 ✓(双色)	✓	✓
11 备注 12	打“✓”为适合于工作		14

Key: 1 - battlefield conditions 2 -infrared 3 - active millimeter waves 4 - infrared/millimeter waves 5 - sunny days 6 - smoky fog, and sand dust 7 - fog 8 - moderate rainfall 9 - chaff jamming 10 - corner reflector of radar 11 - light spots and burning oil 12 - remarks 13 - (dual-spectrum) 14 - "check mark" indicates suitable for operation

3.3. Upgrading the capability of guidance systems as to target discrimination and classification

Since millimeter-wave radar can provide distance information and doppler property signals of targets, can operate in various polarizations, can extract multiple information about frequency spectrum, amplitude, phase, and polarization from the target reflective waves, to supplement insufficiency of infrared systems as to these aspects, therefore the infrared/millimeter wave dual-mode guidance system can acquire more information than the exclusive infrared system to discriminate target properties. The infrared system is high in discrimination rate and low in guidance blind zones; these properties overcome the shortcomings

of active millimeter-waves with large drift due to target scintillation. Thus, discrimination and classification of targets are upgraded and guidance accuracy is enhanced in providing more guidance information, thus greatly upgrading the reliability in operating the guidance system.

3.4. Enhancing the capability of antijamming and anti-invisibility

With the development of invisibility materials and techniques, a single guidance mode is unable to satisfy the battlefield demands against invisibility. The dual-mode guidance system can automatically switch to infrared or millimeter-wave guidance operating mode based on the optical or electronic jamming emitted by the target, thus enhancing the counterjamming capability. The invisibility material will not be able to withstand both the infrared and the millimeter waves. The target coated with absorbent material absorbing electromagnetic waves is certainly a good infrared radiation source. Similarly, the surface against infrared is certainly a good reflector of electromagnetic waves. Therefore, the infrared/millimeter wave dual-mode homing guidance system has higher capability against visibility so that the enemy's camouflage and invisibility are not effective.

As to the foregoing, the overall performance of the infrared/millimeter wave dual-mode combined seeker system is undoubtedly better than a single working mode of infrared or millimeter waves. Therefore the dual mode is recognized as the most promising homing guidance technique.

IV. Analysis of Key Techniques of Dual-Mode Combined Seekers

4.1. Combined technique of sensors with common aperture

One of the key techniques of the IR/mmW dual-mode seeker system is how to combine the infrared optical system and the millimeter-wave antenna into a dual-mode small size energy-concentrated sensor with common aperture.

The wavelengths of the infrared and millimeter waves differ widely; this feature causes great difficulty in designing an optical system with a common aperture. First, these are problems of design, materials, and technique of the dome. Next is the requirement that the optical material should reflect both the infrared and the millimeter waves and sometimes it is reflected from one of the two, but it penetrates the other. In addition, the combination of common aperture is related to the fundamental theory of optics and electromagnetics, as a comprehensive science for designing infrared systems and antenna engineering. This is a difficult technical problem to be closely studied. Only by overcoming this difficult point and developing a dual-mode energy-concentrated sensor with common aperture can the development of infrared/millimeter wave dual-mode seeker proceed.

There are two methods of combining the structure of infrared and millimeter waves, optically; the separated aperture combination and the common aperture combination.

4.1.1. Dual-mode combination of infrared/millimeter wave with separated aperture

Combining of separate aperture is also called the common aiming line or parallel arranged structure type. Its feature is

to separate the visual line (field) of two sensors with aiming line maintained parallel. This structure is easier, as shown in Fig. 1. In information processing, this combination method involves conducting combined data processing of infrared and millimeter-wave information independently acquired by an infrared

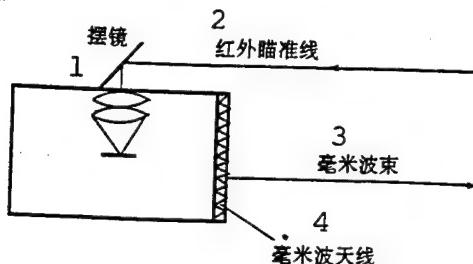


图1 分孔径复合结构

Fig. 1. Combined structural diagram of separated aperture

KEY: 1 - swinging mirror 2 - infrared aiming line
3 - millimeter wave beam 4 - millimeter wave antenna

optical system and a millimeter wave antenna. Due to different installation positions of the optical system and the antenna, infrared and millimeter wave do not affect each other. However, one shortcoming is that each of the infrared and millimeter wave requires a set of scanners, thus, increasing the size and weight of the system with lower cost. Moreover, when detecting the same target, the infrared and millimeter wave systems each has a set of coordinate systems. For unification, alignment errors will be introduced. Thus, the combination of separate aperture is better suited to a ground-based guidance station.

4.1.2. Dual-mode combination of infrared/millimeter wave with common aperture

Both the infrared and millimeter waves are inherently electromagnetic waves, with only different frequencies in the electromagnetic wave spectrum. Millimeter waves have higher similarities with light. The transmission of both infrared and millimeter waves follows the principles of geometric optics. Thus, the infrared optical system and the millimeter wave antenna can be designed into a unified common aperture. This unified apparatus emits electromagnetic energy, and also receives infrared and millimeter wave energy to separate them before transmission to the infrared detectors and millimeter wave frequency mixer.

A unique feature of common-aperture type system is to share a set of optical system antennas so that it is simple to capture signal data of the target, and it is easier to be separated in the signal processor. The common aperture structure of antirefractive Cassegrain antenna/optical component is a good approach. A larger main reflective mirror (and antenna) converges the infrared and millimeter-wave radiation, then reflects the radiation energy onto the subreflective mirror, which can reflect the infrared radiation but let the millimeter waves pass through. Then these two are separated, to be sensed by their respective sensors. We also can use the subreflective mirror to simultaneously reflect infrared and millimeter wave radiation so that after both kinds of radiation energy pass the corrective lens and beam-splitter lens to be outputted to the infrared and millimeter wave detectors or receiving systems, to

complete the target detection task. Fig. 2 shows these two kinds of structures. The IR/mmW dual-mode combined seeker of Bomo Division of General Dynamics applies the Cassegrain optical

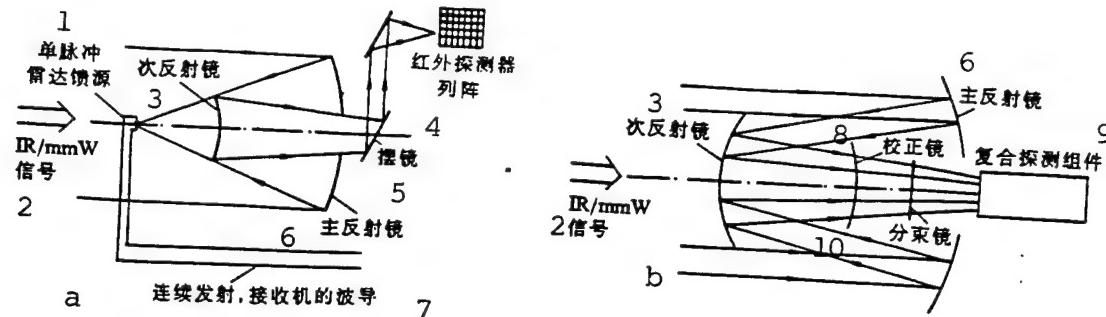


Fig. 2. Diagram of common aperture structure

LEGEND: a - subreflective lens can admit mmW but reflect IR
b - subreflective mirror reflects IR and mmW

KEY: 1 - monopulse radar feed source 2 - signal IR/mmW signal
3 - subreflective mirror 4 - infrared detector array
5 - swinging mirror 6 - main reflective mirror 7 - waveguide
for continuous emission and reception 8 - corrective lens
9 - combined detection component 10 - beam-splitting mirror

system composed of a nonspherical surface main reflective mirror L and an inclined subreflective mirror. An oval flat motor rotates the subreflective mirror to generate tracking error signals of the two modes of the dual-mode seeker. By using this structure, since both the main reflective and the subreflective mirrors can have their surfaces made of, or coated with aluminum, thus more easily realizing higher reflectivity for the IR and the mmW.

There are the following distinct features of the infrared/millimeter wave combination with common aperture:

- 1) Simple scanning system

Application of the common aperture technical is advantageous

to reducing the scanning hardware so that the antenna/optical aperture area is optimal, and it is convenient to maintain the scanning line alignment. The infrared/millimeter dual-mode sensor only requires to be installed on a cardan joint, and the optical axis and the electronic axis coincide with each other. Scanning of both subsystems is easily unified, thus simplifying the scanning system.

2) High detection accuracy

In the infrared/millimeter-wave dual-mode sensor, the optical axis coincides with the electronic axis. When the dual-mode system detects the same target, the coordinate systems of both subsystems coincide with each other without alignment, thus avoiding alignment error for upgraded accuracy.

3) Small size, light weight, and low cost

4) Higher fabrication difficulty, especially two particular wavebands should be made to pass through the dome.

Since the dual-mode combination performance of the infrared/millimeter wave with common aperture is excellent, such dual mode is highly regarded. In recent years, research studies with outstanding results were attained in the United States, the U.K., Japan, and China. Generally, there are the following types of combined common apertures:

i. Combination of Cassegrain optical system and cassegrain antenna

ii. Combination of Cassegrain optical systems and parabolic antenna

iii. Combination of Cassegrain optical system and monopulse array antenna, and

iv. Combination of Cassegrain optical system and phase control array antenna.

Figs. 3 and 4 show two fundamental structures that can be adopted for a combined seeker with common aperture.

4.2. Highly-accurate technique of stability position marker

Highly accurate stability system is one of key components of combined seekers. The system has higher requirements than the stability of single-mode seeker. The IR/mmW dual-mode common-aperture sensor and the combined search and tracking mechanism should be installed on a stable universal joint; this requires high stability precision to ensure measurement and tracking precision of the seeker system. Therefore, the stability system of a combined seeker should be based on different guidance modes for applications in different model numbers by selecting the best scheme of the stability system. Generally there are the following types of the universal-joint stabilization system that can be chosen:

(1) Dynamic gyroscopic frame gimbal stabilization platform

The gyroscopic frame gimbal platform with two degrees of freedom can be divided into the external frame type, internal frame type, and servo-connection type structures. This type of stabilized system is structurally simple, adaptable to tactical missiles with not very high guidance accuracy, as well as search and tracking accuracy. Placing the combined sensor onto a

universal joint frame makes it possible to accomplish detection, search, and scanning of targets.

(2) Stable platform type structure

By placing the combined sensor mechanism onto a stable platform, the special stabilization of the optical axis can be realized. This approach is stable and reliable, capable of completely eliminating error due to unstable interference caused by carrier movement; however, the equipment is complex and its costs are high

(3) Gas-floating gyroscopic structure

The gas-floating gyroscopic type structure has significant features of high g-load endurance, suitable to position marking of the combined seeker in terminal guidance artillery rounds. Since the seeker in the terminal-guidance round generally requires high capability of withstanding more than 12,000g, to be free from damage on the gas-floating gyroscopic support at high g's, while maintaining good working performance, this is a more ideal structural scheme of dual-mode combined seeker for terminal-guidance artillery rounds. However, this requires high precision, complex structure, and high technical difficulty.

Fig. 5 shows a structure type of dual-spectrum infrared combined seeker. Fig. 6 shows a structure type of infrared/millimeter-wave dual-mode combined seeker.

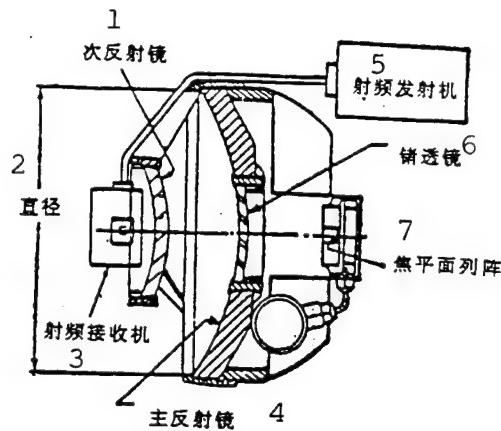


Fig. 3. Structural diagram of IR/mmW common aperture seeker

KEY: 1 - subreflective mirror 2 - diameter
 3 - radiofrequency receiver 4 - principal reflective mirror
 5 -radiofrequency emitter 6 - germanium lens 7 - focal-plane array

4.3. Real-time target recognition of the combined seeker system, and information merge processing technique

The real-time target recognition, mode decision-making, and information-merged processing is one of the key techniques of infrared/millimeter wave seekers; the technique includes comprehensive recognition method of the target, optimal decision-making method, information merge processing, optimized filtration method, and real-time processing technique in the combined variable target/background conditions and environmental conditions of multiple sensor signals.

For statistical discrimination in a sensor channel, it is required to select the feature capable of separating the target and background to the greatest extent. However, with respect to

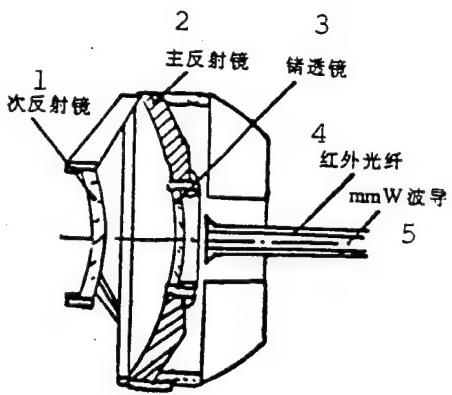


Fig. 4. Another structural diagram of
IR/mmW common aperture seeker

KEY: 1 - subreflective mirror 2 - principal reflective mirror
3 - germanium lens 4 - infrared optical fiber 5 - mmW
waveguide

the infrared/millimeter-wave dual-mode combined sensor system, it is required to select features in two channels. Generally, there are two signal processing methods (concentrated type and distributed type) as shown in Fig. 7.

The distribution type executes preprocessing, discrimination and classification for each sensor channel. Then, all outputs from the preclassifier are conducted weighted processing in the classifier to generate a dual-mode output. The concentrated type executes the classification operation on all input data of the sensor. Thus, the selection feature should be in a unified characteristic space. Since this type does not lose its useful information before decision making, the highest performance can be realized. However, from the approach of realization, the distributed type processing is easier to be carried out, and can conveniently merge the output of two channels of a single-mode

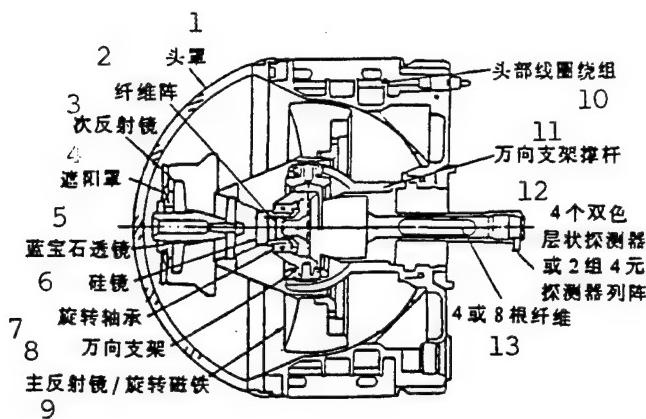


Fig. 5. IR dual-spectrum scan imaging seeker
 KEY: 1 - top shade 2 - fiber array 3 - subreflective mirror
 4 - shading cover 5 - sapphire lens 6 - silicon lens
 7 - rotary bearing 8 - universal-joint 9 - principal
 reflective mirror/rotating magnet 10 - top coil winding
 11 - support rod of universal joint 12 - dual-spectrum
 detectors or two sets of four-element detector array 13 - four
 or eight fibers

sensor, not requiring classification operation in a complex unified feature space.

How to discriminate targets by using a dual-mode signal is a task that the information-merge technique should accomplish. There are the five following conditions for carrying out the information merge: a. multisensor information, b. environmental data c. data bank, d. algorithmic software, and e. hardware.

The infrared/millimeter-wave dual mode sensor information merge processing takes place in a processor by using the function of combinatorial logic. By using input from the algorithm of a single sensor, weighted processing is conducted. Then, by using the data merging algorithm, the logical results are

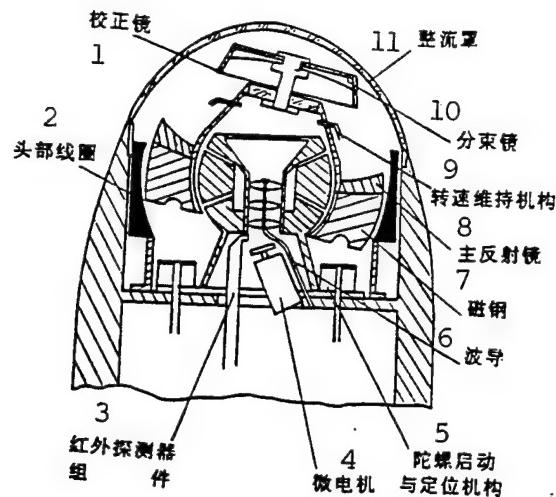


Fig. 6. Structural diagram of IR/mmW dual-mode seeker
 KEY: 1 - corrective lens 2 - top winding 3 - component of infrared detector 4 - miniature motor 5 - rotor starting and positioning mechanism 6 - waveguide 7 - magnetic steel 8 - principal reflective mirror 9 - rotational speed maintenance mechanism 10 - beam-splitting mirror 11 - dome
 discriminated. Not only by using an AND gate and an OR gate, the target detection probability (PD) can be upgraded, and the false-alarm probability (PFA) can be reduced. Combinatorial logic should be added in order to attain satisfactory results, as shown in Fig. 8.

The purpose of logical processing is to separate the target from background to the greatest extent. To do this, we should understand the target, the background, and their features, in order to acquire data on these features. However, it is very difficult to obtain these data. Generally, a statistical software algorithm is used to solve the problem.

Generally speaking, the real-time target discrimination and

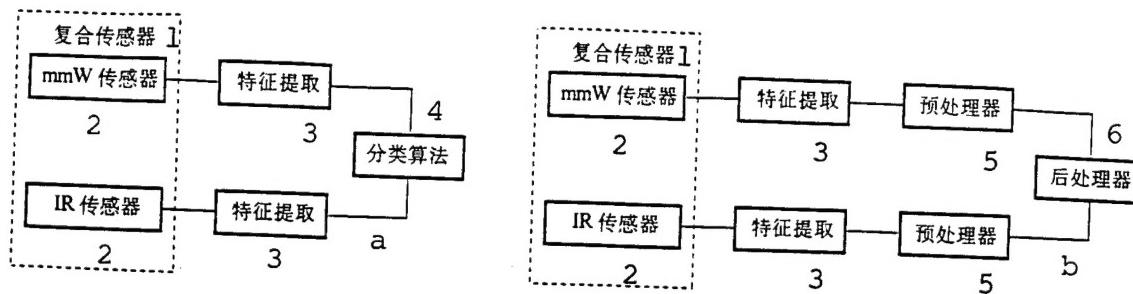


Fig. 7. Block diagram of signal processing mode
 LEGEND: a - concentrated-type processing approach
 b - distributed-type processing approach

KEY: 1 - combined sensor 2 - sensor 3 - extraction of features 4 - classification algorithm 5 - preprocessor
 6 - postprocessor

the information-merge processing of a dual-mode seeker are a complex information processing procedure. In-depth exploration and research are required.

4.4. General technique of combined seeker head system

To develop a high-quality combined seeker satisfying the requirements of tactical indicators, we should develop the research on overall techniques of the combined seeker system, such as methods of capturing the target and attacking the target; analysis and comparison of various approaches of combined seeker; technical resolution of different schemes; overall optimization design schemes of the combined seeker; study of system electromagnetic compatibility and antijamming technique; testing regimes and methods of system performance of the combined seeker, and study of the evaluation criteria; study of simulation technique of semi-real objects; study of the radiation properties and refection properties of targets and backgrounds; and study of

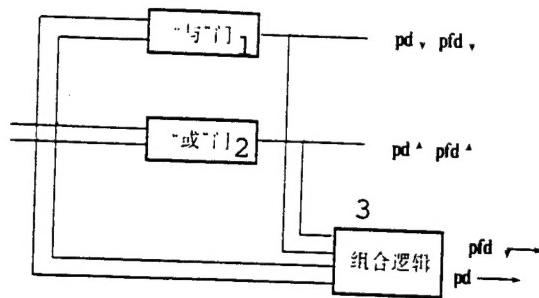


Fig. 8. Logic diagram of dual-mode signal processing
 KEY: 1 - AND gate 2 - OR gate 3 - combinatorial logic

the atmospheric transmission properties. With these studies, an effective and rational overall execution scheme can be formulated for the combined seeker.

V. Conclusions

The combined seeker is an important developmental direction; the dual-mode combined seeker is an advanced design concept proposed in recent years. The dual-mode concept has advantages of both frequency spectral properties. In tactical applications, the combined seeker will greatly upgrade the antijamming and all-weather performance of the homing-guidance system, in addition to the capability of anti-invisibility and recognition of targets, upgrading of guidance accuracy, and extension of effective range. Therefore, studies on the combined seeker technique should be emphasized to vigorously develop the advanced single-mode seeker, such as graphic guidance (television and infrared imaging), and millimeter-wave guidance. Based on these studies, technical

development studies of dual-mode seeker should be actively promoted to solve key technical problems, to accumulate experience, to upgrade the technical reserves for a good technical foundation. Once these are done, development of models can be carried out.

The article was received for publication on January 10, 1994.

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